

White Dwarfs: Contributors and Tracers of the Galactic Dark-Matter Halo

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We examine the claim by Oppenheimer et al. (2001) that the local halo density of white dwarfs is an order of magnitude higher than previously thought. As it stands, the observational data support the presence of a kinematically distinct population of halo white dwarfs at the >99% confidence level. A maximum-likelihood analysis gives a radial velocity dispersion^a of $\sigma_U^h = 150^{+80}_{-40}$ km s⁻¹ and an asymmetric drift of $v_a^h = 176^{+102}_{-80}$ km s⁻¹, for a Schwarzschild velocity distribution function with $\sigma_U:\sigma_V:\sigma_W = 1:2/3:1/2$. Halo white dwarfs have a local number density of $1.1^{+2.1}_{-0.7} \times 10^{-4}$ pc⁻³, which amounts to 0.8^{+1.6}_{-0.5} per cent of the nominal local dark-matter halo density and is 5.0^{+9.5}_{-3.2} times (90% C.L.) higher and thus only marginally in agreement with previous estimates. We discuss several direct consequences of this white-dwarf population (e.g. microlensing) and postulate a potential mechanism to eject young white dwarfs from the disc to the halo, through the orbital instabilities in triple or multiple stellar systems.

1 Introduction

Recently, Oppenheimer et al. (2001; O01 hereafter) found 38 white dwarfs (WD) in a sample of 99 high proper motion WDs, which were claimed to have kinematics inconsistent with that of both the old stellar disc and the thick disc, and therefore form a newly discovered halo population with an inferred density at least an order of magnitude higher than previously thought (e.g. Gould et al. 1998). Reid et al. (2001) have criticized this result and conclude that these WDs form the high-velocity tail of the thick disc, based on a comparison of their $U-V$ velocity distribution with that of M-dwarf stars. Unfortunately, neither conclusion is statistically supported.

In this proceeding, we discuss a maximum-likelihood analysis of the complete sample of 99 WDs and derive the local phase-space density of thick-disc and halo WDs. This then allows us to draw more robust conclusions. For a discussion of the selection of the sample, we refer to O01. Details of the likelihood analysis and phase-space density estimate can be found in Koopmans & Blandford (2001; KB01 hereafter). For clarity, throughout the proceeding the low- and high-velocity dispersion components are referred to as the thick-disc and halo population, respectively. This does not imply that all WDs could not have originated from the thin or thick disc (e.g. Hansen 2001; KB01).

^aHereafter, if not otherwise indicated, errors give the 90% statistical confidence level.

2 The White–Dwarf Velocity Distribution Function

We model the local (\vec{x}_0) velocity distribution function (VDF) as a superposition of two Schwarzschild (i.e. Maxwellian) VDFs, i.e. $f_B(\vec{x}_0, \vec{v})$. We assume a constant space density of WDs throughout the surveyed volume. Each component has two free parameters, the radial velocity dispersion (σ_U) and the asymmetric drift (v_a). In addition, the parameter r_n is the ratio of the thick-disc to halo WD number densities (n). We assume that the vertex deviations are zero and that the ratios of the radial (U), azimuthal (V) and vertical (W) velocity dispersions of the ellipsoidal VDFs are $\sigma_U:\sigma_V:\sigma_W=1:2/3:1/2$, in agreement with observations (see KB01 for references). The probability that an observed WD with a velocity vector on the sky, $\vec{p} = (v_l, v_b)$, is drawn from this VDF becomes $P = \int_{\infty}^{\infty} (v_l^2 + v_b^2)^{3/2} f_B(\vec{v} = \vec{p} + v_r \hat{r}) dv_r / \int_{\mathcal{V}} (v_l^2 + v_b^2)^{3/2} f_B(\vec{v} = \vec{p} + v_r \hat{r}) d^3v$, where v_r is the radial velocity along the line-of-sight and v_l and v_b are the velocities projected on the sky in Galactic coordinates. This assumes that the WDs are all proper-motion limited ($\sim 90\%$ are). \mathcal{V} is then the velocity space in which the WDs could have been found, given the restriction that $v_l^2 + v_b^2 > (\mu_0 r)^2$, where r is the distance to the WD and μ_0 is the survey’s lower limit on the proper motion ($\mu_0 \sim 0.33'' \text{ yr}^{-1}$). For the $\sim 10\%$ magnitude limited WDs, we find that their maximum detection volumes (V_{\max}) are nearly identical. For these, we modify the likelihood function, although the differences in parameter estimates are within the errors quoted below. By varying the five free parameters and optimizing the log-likelihood, $\mathcal{L} = \sum_i \log(P_i)$, of the sample, we solve for their most likely values and their error range. The results (excluding 3 thin-disc WDs) are: (a) $\sigma_{U,d} = 62^{+8}_{-10} \text{ km s}^{-1}$, (b) $\sigma_{U,h} = 150^{+80}_{-40} \text{ km s}^{-1}$, (c) $v_{a,d} = 50^{+10}_{-11} \text{ km s}^{-1}$, (d) $v_{a,h} = 176^{+102}_{-80} \text{ km s}^{-1}$ and (e) $r_n = 16^{+30}_{-11}$ (KB01).

3 The Local Halo White–Dwarf Density

To normalize the local phase-space density of halo plus thick-disc WDs, i.e. $n_{0,\text{WD}}^{\text{td+h}} \cdot f_B(\vec{x}_0, \vec{v})$, it remains to estimate their local density, $n_{0,\text{WD}}^{\text{td+h}}$. We do this in the conventional way, by summing the $1/V_{\max}$ values of the halo plus thick-disc WDs, where V_{\max} is the smallest of the two volumes in which a WD could have been detected, when limited either by its proper motion or by its magnitude (e.g. O01; KB01). We find that $\sim 90\%$ of the WDs are proper-motion limited and three WDs are very likely associated with the thin disc. The latter WDs are removed from the sample, as we are only interested in the halo plus thick-disc density, for which we determined the VDF. We find $n_{0,\text{WD}}^{\text{td+h}} = (1.9 \pm 0.5) \times 10^{-3} \text{ pc}^{-3}$, of which $n_{0,\text{WD}}^{\text{h}} = 1.1^{+2.1}_{-0.7} \times 10^{-4} \text{ pc}^{-3}$ belongs to the halo, given r_n found from the maximum-likelihood analysis of the sample. The local halo plus thick-disc density estimate agrees within $\sim 1 \sigma$ with the estimate from Reid et al. (2001). The halo density is $5.0^{+9.5}_{-3.2}$ times

higher than the best previous estimate of $\tilde{n}_{0,\text{WD}}^{\text{h}} = 2.2 \times 10^{-5} \text{ pc}^{-3}$ from Gould et al. (1998), inferred from the mass function of halo stars. Locally, our density estimate amounts to $0.8_{-0.5}^{+1.6}\%$ of the nominal local dark-matter halo density of $8 \times 10^{-3} M_{\odot} \text{ pc}^{-3}$ (Gates et al. 1995).

4 The Global Halo White-Dwarf Density

Given the *local* phase-space density of halo plus thick-disc WDs and a potential model for the Galaxy, we can estimate the *global* white-dwarf density in a large part of the Galactic halo, using Jean's theorem (e.g. May & Binney 1986). For simplicity, we assume a spherical logarithmic potential, $\Phi(r) = v_c^2 \ln(r/r_c)$, with rotation velocity $v_c = 220 \text{ km s}^{-1}$ and a solar radius of $r_c = 8 \text{ kpc}$. For the halo WDs, which are less affected by the disc/bulge potentials this is probably a reasonable assumption, although this does not hold for the lower-velocity thick-disc WDs. A analytic expression for the phase-space density of halo WDs can then be derived for any point in halo that is in dynamic contact with the Solar neighborhood (KB01). From this phase-space density model, we find an oblate ($q = (c/a)_\rho \sim 0.9$) distribution of halo WDs with a total mass inside 50 kpc of $\sim 2.6 \times 10^9 M_{\odot}$ and a radial mass profile $n(r) \propto r^{-3.0}$. We expect q to decrease further if a proper flattened Galactic potential is used. This halo WD mass amounts to $\sim 0.4\%$ of the total Galactic mass inside 50 kpc, $\sim 4\%$ of the Galactic stellar mass, or $\Omega_{\text{WD}} \sim 10^{-4}$. Including disc WDs, the total mass of WDs in the Galaxy is $\sim 9\%$ of the stellar mass, in agreement with standard population synthesis models (Hansen 2001; KB01).

5 The LMC Microlensing Optical Depth

Given our analytic expression of the halo WD phase-space density, we can integrate over the line-of-sight towards the Large Magellanic Cloud (LMC) to estimate the microlensing optical depth of this population. We find $\tau_{\text{WD}}^{\text{h}} \sim 1.3 \times 10^{-9}$, which is $\sim 10^2$ times lower than observed (Alcock et al. 2000). The thick-disc WDs have a ~ 3 times higher optical depth. The integrated halo plus thick-disc WD optical depth is therefore still 1–2 orders of magnitude too small.

6 Conclusions, Discussion & Future

Modeling of the local phase-space density of halo plus thick-disc WDs indicates that there is a population of pressure-supported halo WDs with a *local* density $5.0_{-3.2}^{+9.5}$ times higher than previously estimated, although globally ($r \lesssim 50 \text{ kpc}$) the mass contribution is negligible ($\sim 0.4\%$). Both the low- and high-velocity populations have similar color, magnitude and ages distributions (Hansen 2001;

KB01). Two particularly interesting surveys to search for more high proper motion WDs are: (i) a wide survey with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope, which we estimate should find ~ 5 WDs (KB01) and (ii) a similar survey as that by O01 towards the Galactic anti-center to constrain the WD velocities perpendicular to the Galactic plane.

The white-dwarf data set from O01 and results derived from it (i.e. our most likely model) have met a number of internal and external consistency checks (KB01) and agree with *all* observational constraints (e.g. direct observations, metal pollution of the ISM, microlensing, etc.) known to us. The color-color relation of the WDs shows them to be quite young (Hansen 2001) and have a birth rate roughly that expected from Galactic population synthesis models (KB01). Why then do a large fraction of these WDs have such high spatial velocities? *To explain this we postulate the following; the majority of high-velocity WDs in the Galactic halo originate from multiple* (i.e. $N \geq 3$) *stellar systems in the Galactic disc. In case of a triple stellar system, stellar evolution (i.e. mass loss and/or transfer) of the (probably more massive) inner binary stars changes the ratios of orbital periods and eventually destabilizes the system. At that point, the lightest star, a WD in the inner binary, is ejected from the system into the halo – possibly through a slingshot of the outer star – leaving behind a recoiled compact binary* (KB01). This postulate implies a direct relation between the radial surface density of the stellar disc, the star-formation rate and population synthesis models, which all seem to be in agreement (KB01), *but* still need considerable study.

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